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14. ABSTRACT

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A 55 GHz Bandpass Filter Realized With Integrated TEM Transmission Lines

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***Abstract*— A compact 4-pole bandpass filter centered at 55 GHz with a 13.6% bandwidth is realized using an integrated three dimensional microfabrication process. The filter has an almost exact match to the design simulations except for a shift in the center frequency that is less than 1.3%. Measured insertion loss is 2.4-3.5 dB. The filter is very compact, measuring less than 0.86 mm ($\approx \lambda/6$) by 1.9 mm ($\approx \lambda/3$) by 0.3 mm ($\approx \lambda/15$). This filter clearly demonstrates the potential of three dimensional microfabrication processes for the realization of millimeterwave filters.**

***Index Terms*— Millimeter wave filters, Millimeter wave circuits, Resonators, Micromachining, Microelectromechanical Systems**

I. Introduction

Increasing use of the microwave spectrum combined with growing demand for high bandwidth secure communications is pushing users towards greater use of millimeterwave frequencies. Traditionally, filters in this frequency range have been made with waveguides due to their low losses. However, compact, integrated solutions are desired to reduce system size, weight, and cost.

The advent of three dimensional micromachining processes over the past decade has opened up the potential for integrated rectangular coaxial (recta-coax) lines and striplines [1]. These processes allow the precise physical realization of the design models used for finite element simulations. In addition, micromachining processes produce numerous copies of a device with minimal variation. The result is that the design process is simplified and the realized filters are essentially equivalent, eliminating the need for time consuming and costly post fabrication tuning.

The compact nature of the filters does limit the resonator quality factor which impacts the insertion loss of the filter. However, with low-loss metalizations, currently available fabrication processes can yield integrated coaxial resonators with quality factors in excess of 200 at 30 GHz [1]. It is therefore possible to realize low loss integrated filters in a very compact space. We demonstrate this potential through the fabrication of a 55 GHz bandpass filter with dimensions smaller than $\lambda/6$ by $\lambda/3$ by $\lambda/15$. The realized 4-pole filter has a bandwidth of 13.6% with a minimum insertion loss of 2.4 dB.

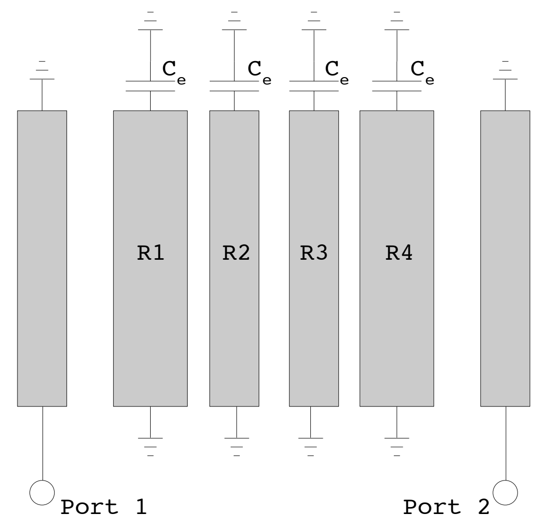


Fig. 1. Schematic illustration of a 4-pole combline filter.

II. Filter Design

A combline filter topology, shown in Fig. 1, was chosen for this demonstration for several reasons. First, it is very compact. The admittance and impedance inverters are implemented using resonators that are shorted at one end and capacitively-loaded at the other end. For the current design, the resonators are nominally $\lambda/8$ long. Second, since the resonators are all shorted, they can be implemented as cantilevers attached to the side wall and thus there is no need for a dielectric support. Third, the resonators are configured so that the capacitively loaded ends are all on the same side of the filter. While the present design is not tunable, future work is aimed at adding variable capacitors to create a tunable filter and the arrangement in this design lends itself to this goal. Fourth, this design is relatively open. Open structures are easier to realize in sacrificial etch type micromachining processes. Finally, this filter type has very broad lower and upper stop bands.

The combline filter has been widely used, and detailed design equations are available from Matthaei, Young, and Jones [2]. The design process requires selecting the filter design parameters, calculating the end loading capacitance (C_e

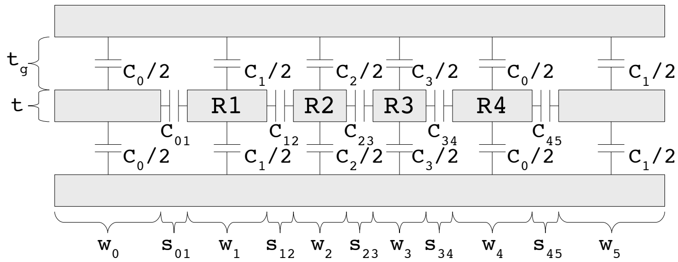


Fig. 2. Illustration of the filter cross section. Labels for the capacitor to ground, inter-line capacitors, and filter dimensions are.

TABLE I

FILTER CAPACITANCES AND DIMENSIONS.

j	C_j/ϵ	w_i	C_{ej}	j	$C_{j,j+1}/\epsilon$	$s_{j,j+1}$
0,5	5.816	0.194	0.039	0,4	1.718	0.046
1,4	3.301	0.091	0.039	1,3	0.464	0.128
2,3	4.237	0.108	0.039	2	0.39	0.143

$t = 0.05 \qquad t_g = 0.097$

(All dimensions in mm, capacitances in pF)

shown in Fig. 1), calculating the line-to-ground and interline capacitances (C_j and $C_{j,j+1}$ shown in Fig. 2) and then using these to calculate the line dimensions. For this implementation, a four pole, 0.5 dB, equal ripple design was chosen. The resonator lengths were set to $\lambda/8$ (0.682 mm at 55 GHz) and the the line dimensions were calculated using the procedure detailed in [2]. Table I provides the calculated capacitances and dimensions. Once the initial design was completed, a three dimensional model was created using Ansoft HFSS [3]. Tuning was done through iterative simulation to get the correct end-loading capacitance. The resulting filter design has a simulated bandwidth of 13.6% instead of the originally desired 10% bandwidth. Parasitic bandwidth expansion in combline filters has been studied previously [4], and future designs will correct this error. However, for this demonstration filter, the change in the bandwidth was not considered critical. All of the simulations were done for a nickel structure since this was the only material available in the fabrication process.

Particular interest was placed on the impact etch holes have on filter performance. The etch holes are required due to the sacrificial etching process used during fabrication. Both the time required for the sacrificial etch and the quality of the etch clean out are dependent upon the access that the liquid etchant has to the interior of the structure. As a result, large closely spaced holes are desired. Unfortunately, these holes interfere with the current flow along the surface that serves as the filter ground plane. Numerous simulations showed that etch holes could be liberally used, but that their location and shape can have a major impact on filter performance. Essentially, the holes must be placed so that they do not interfere with currents flowing on the ground. This allows very large holes to be designed into the ends of the filter where there is essentially no current flow. However, it does mean that long etch holes should be avoided. Fortunately, with careful attention to the placement of the etch holes their impact can be essentially eliminated. An isometric view of the final filter model including etch holes but excluding probe ports is provided in Fig. 3. The simulated filter performance for the filter before and after etch holes were introduced is shown in Fig. 4. This final filter design measures 0.86 mm by 1.857 mm by 0.296 mm and thus requires 1.6 mm^2 of die space. Fig. 5 provides a comparison of the filters performance if it were fabricated in nickel, gold, or copper.

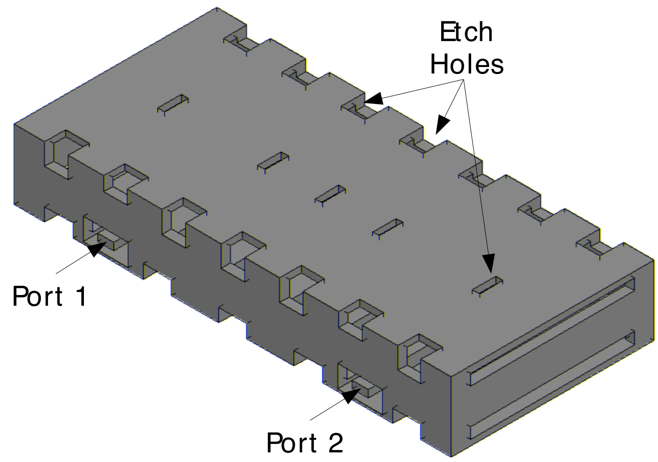


Fig. 3. Final physical filter design. The two ports are on the front face. Etch holes have been liberally placed on all surfaces except the bottom of the filter.

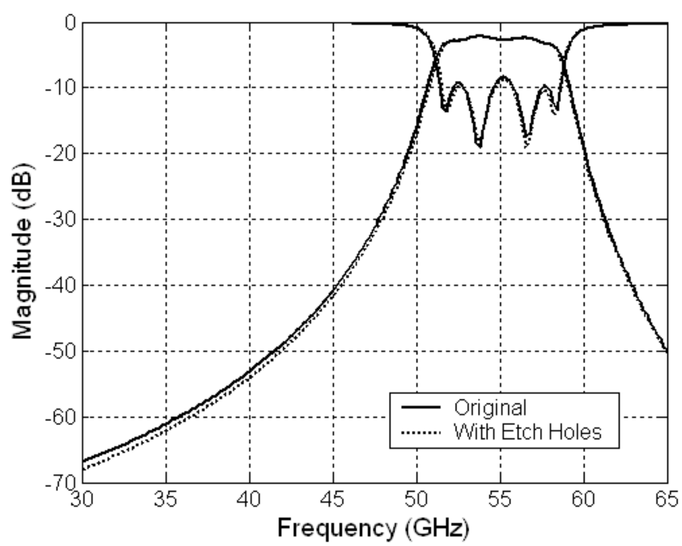


Fig. 4. Simulated insertion loss and return loss of the filter before etch holes were added and with the final configuration.

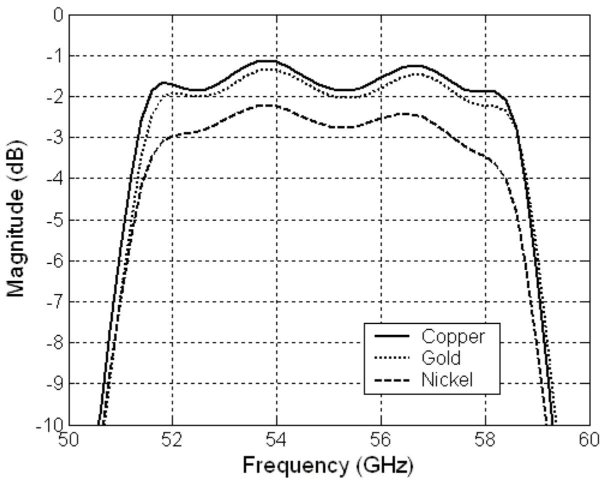


Fig. 5. Simulated filter insertion loss for filters fabricated with three different metals.

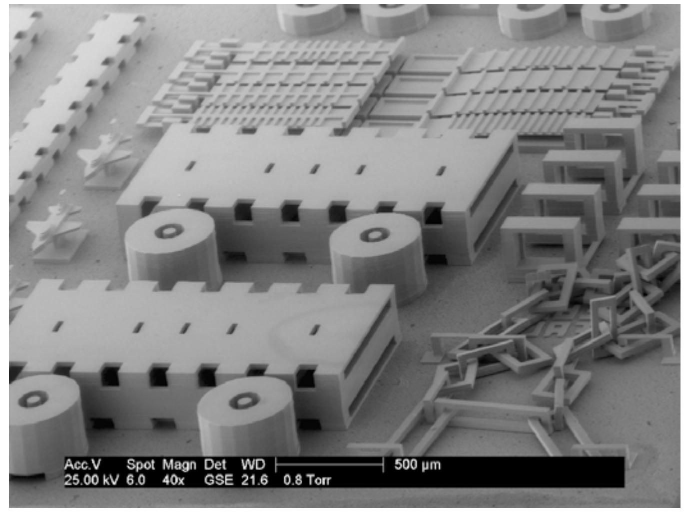


Fig. 6. A scanning electron micrograph (SEM) picture of two fabricated filters. The two circular structures (lower left) are probe ports added to the filter to facilitate measurement with ground-signal-ground probes.

III. Results

The filter was fabricated under a foundry contract. Designs were submitted by the Antenna Technology Branch (AFRL/SNHA) to Microfabrica, Inc. and fabricated in the EFAB^{TM} process [5], [6]. The final process for these filters has 26 nickel layers and allowed structures up to 296 μm tall to be fabricated. The fabricated filters are composed entirely of nickel as it was the only material available at the time of fabrication. Two filters were included on each die. These filters can be seen in Fig. 6. The two large circular structures in front of the filter are omni-directional probe pads that were added to facilitate probing with ground-signal-ground probes. As is clear in Fig. 6, each die site has numerous additional devices and test structures located near the filters. It is not necessary to include these structures in any simulation or modeling because the ground enclosure of the filter shields it from nearby circuit elements.

Measurements were taken on an Agilent E8361a vector network analyzer (VNA). A Thru-Reflect-Line (TRL) VNA calibration was performed over the 30 GHz to 67 GHz frequency range using calibration standards that were fabricated on the die with the filters. The standards consist of a 0.4 mm through line, a 0.2 mm shorted line, and a 1.336 mm through line. The TRL lines include a transition from a 50 Ω circular coax to 50 Ω recta-coax line. Utilizing this TRL calibration, the measurement plane is the same as was used for simulations. Measurements were taken on both filters from multiple die sites. Fig. 7 provides a comparison between a typical measured filter and the simulated scattering parameters. Agreement between the finite element simulations and the measurement is very good. The center frequency of the measured filters is 1-1.5 % off from the HFSS simulations. The measured bandwidth and roll off are exactly in line with predictions. The measured ripple is between 0.5 and 1 dB and the minimum insertion loss is 2.4 dB. The discrepancy in the center frequency is most likely due to a slight difference between the expected and realized end loading capacitance.

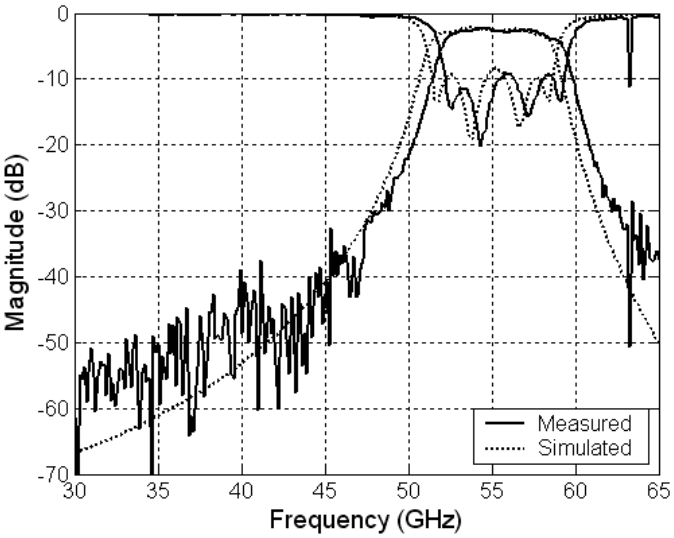
The unloaded quality factor for the resonators can be calculated using the measured filter performance as [2]

$$Q_u = \frac{8.686 C_n}{w \Delta L_A}, \tag{1}$$

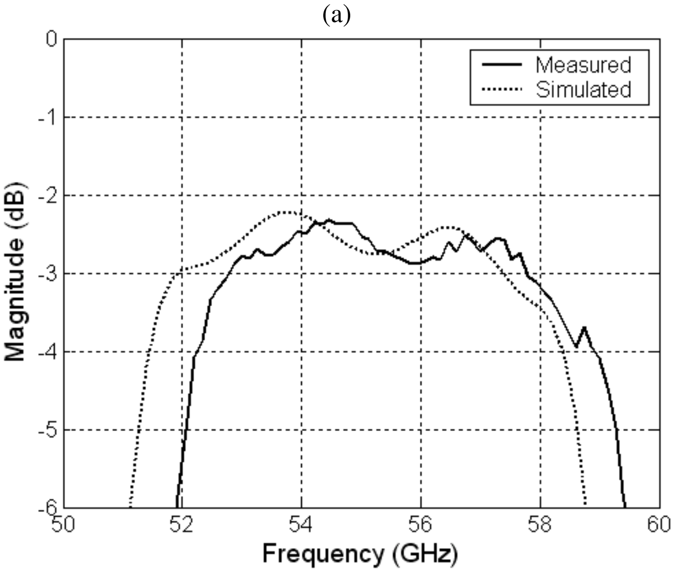
where $C_n = 3.035$ is a coefficient dependent upon the type and order of the filter, $w = 0.136$ is the fractional bandwidth of the filter, and $\Delta L_a = 2.75$ is the mid-band (55 GHz) filter loss in dB. For this filter, the unloaded resonator quality factor is 70.5. The mismatch loss is not included in this calculation, and would raise the quality factor somewhat. The calculated quality factor of a 100 μm wide 50 Ω recta-coax line with the same thickness and gap is 77.1, which is in good agreement. Going to a copper metallization would approximately double the resonator quality factor and thus cut the insertion loss in half to ≈ 1.3 dB.

IV. Discussion

New micromachining processes have the potential to dramatically simplify the design of integrated millimeterwave systems by allowing the use of enclosed TEM transmission lines with low loss. This has been demonstrated here with the successful first pass realization of a 4-pole, 55 GHz, bandpass filter. The filter shows excellent agreement with the simulated design and is not sensitive to surrounding structures. Fabricated filters were measured on multiple die sites with only minor variance. For relatively wideband filters ($w > 0.1$) the filters can be designed so that tuning is not required. For narrow band filters, however, further investigations will be needed to determine the cause of the $\approx 1\%$ shift in the center frequency of the filter. The overall performance of the filter will be significantly improved by the use of copper, gold, or silver metallization. In addition, the total height of the filter can be



(a)



(b)

Fig. 7. Measured and simulated scattering parameters. The measured filter is offset in frequency by approximately 1% from the simulated design. (a) Insertion loss and return loss. (b) A close up of the filter insertion loss in the pass band.

increased to further reduce losses. Both of these improvements are possible with processes that are becoming available today.

Acknowledgment

The views expressed in this article are those of the authors and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the U.S. Government. This document has been cleared for public release: Distribution Unlimited; ESC-06-0060.

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References

[1] J. Reid, E. Marsh, and R. Webster, “Micromachined rectangular coaxial transmission lines,” *IEEE Transactions on Microwave Theory and Techniques*, Submitted for publication, Dec. 2005.

[2] G. Matthaei, L. Young, and E. Jones, *Microwave Filters, Impedance-Matching Networks, and Coupling Structures*. Artech House Books, 1980.

[3] Ansoft high frequency structure simulator, version 9.0. [Online]. Available: www.ansoft.com

[4] I. Shapir, V. A. Sharir, and J. Daniel G. Swanson, “TEM modeling of parasitic bandwidth expansion in combline filters,” *IEEE Transactions on Microwave Theory and Techniques*, vol. MTT-47, no. 9, pp. 1664–1669, September 1999.

[5] A. Cohen, G. Zhang, F. Tseng, F. Mansfield, U. Frodis, and P. Will, “EFAB: Rapid low-cost desktop micromachining of high aspect ratio true 3-D MEMS,” in *IEEE International Conference on Micro Electro Mechanical Systems*, January 1999, pp. 244–251.

[6] [Online]. Available: www.microfabrica.com